



EE 330

# Engineering Electromagnetics

**Lecture 1**

**EE 330**  
**ENGINEERING ELECTROMAGNETICS**  
 10:10-11:00 MWF 160 Willard

**Topics:** This course provides electrical engineering students with an understanding of fundamental electricity and magnetism concepts and enables them to use these concepts in applications.

**Instructor:** Tim Kane, 3-8727, [tk7@psu.edu](mailto:tk7@psu.edu)  
 Wed. and Thurs., 1-3 PM in 213 EE East, or by appointment...

**Prerequisites:** MATH 230 or 232, EE 210. Also try to remember your Physics ☺

**Text:** *Fundamentals of Applied Electromagnetics, 6<sup>th</sup> Ed.*, by F.T. Ulaby et al. 2010.

**Suggested:** Daku, B., *MATLAB Tutorial CD: Learning MATLAB Superfast*, Wiley, 2005.

**Course Requirements and Grading Policy:**

15% Homework  
 15% Labs and Recitation  
 5% Class participation  
 20% Exam #1 (Wednesday night, 22 February, 6:30 PM to 7:45 PM, in 112 Kern)  
 20% Exam #2 (Wednesday night, 4 April, 6:30 PM to 7:45 PM, in 22 Dieke)  
 25% Comprehensive Final Exam  
 100% TOTAL

**Recitation Sections (Labs in 304 Hammond)**

- 1) R 10:10 A - 12:05 P 105 EEW
- 2) T 12:20 P - 2:15 P 201 EEW
- 3) R 2:30 P - 4:25 P 107 EEW
- 4) T 10:10 A - 12:05 P 201 EEW

**TAs:**

TI: Chris Curwen [cac5378@psu.edu](mailto:cac5378@psu.edu)  
 TA: Hee Jung Shin [hns146@psu.edu](mailto:hns146@psu.edu)

**Homework:**

Homework is to be turned in by 4 pm on the due date in the homework slot outside of 121 EE East. You are to use the "E E 330 Homework cover page" provided to you within Angel. Labs are to be turned in electronically via the Drop Box set up for that purpose on Angel. Completed labs are due 1 week from assignment date.

**MATLAB:**

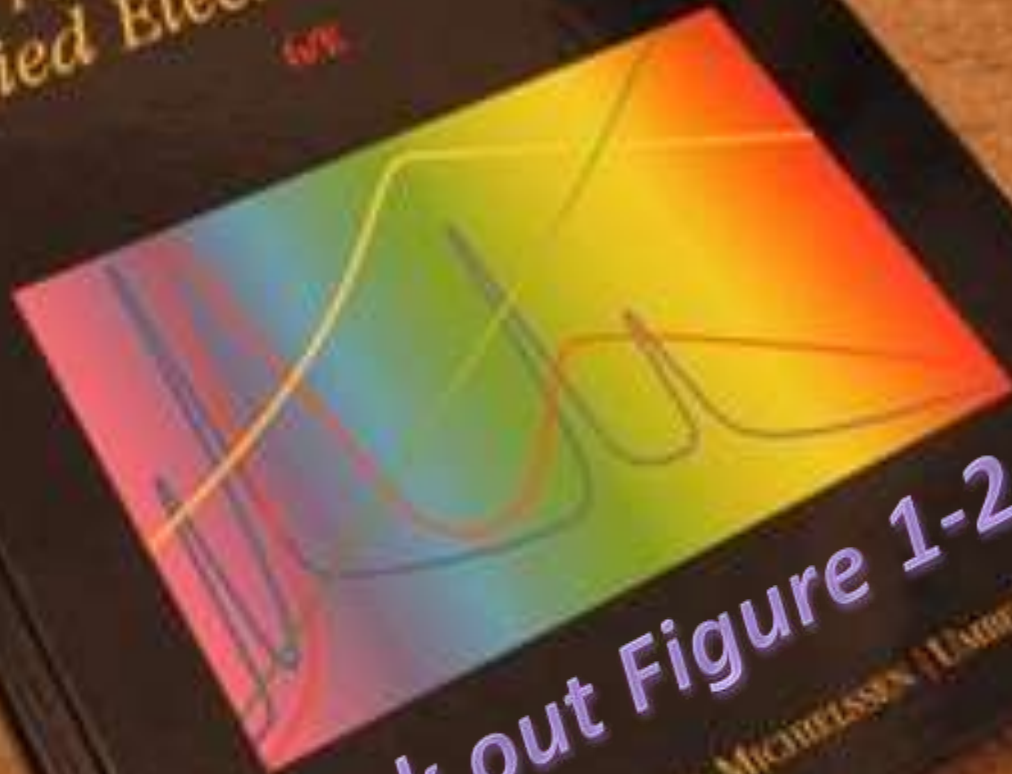
The course will employ MATLAB in lectures, homework, and labs. We feel that using MATLAB will help you to visualize the complex math used in EM and to explore applications more in depth. In addition, by the end of the course you will have in your "toolbox" a very versatile tool that can be used in other classes (particularly at the 400 level) and familiarity with an industry-standard math package that will help you when you look for jobs. It is incumbent on you to become comfortable with MATLAB using the tutorials provided and through the labs.

	Date	Topics	Comments / Reading
1	9 Jan.	Introduction	1-1 thru 1-3
	11 Jan.	"	1-4 thru 1-7
	13 Jan.	Transmission Lines	2-1, 2-2
2	16 Jan.	No Class	----- Lab: Intro
	18 Jan.	(more) T-Lines	2-3 thru 2-5
	20 Jan.	"	2-5 thru 2-7
3	23 Jan.	"	2-8, 2-9
	25 Jan.	"	2-10
	27 Jan.	"	2-11, 2-12
4	30 Jan.	Vector Analysis	3-1 thru 3-3 Lab: Analyzer This
	1 Feb.	"	3-4, 3-5
	3 Feb.	"	3-6, 3-7
5	6 Feb.	Electrostatics	4-1 thru 4-3
	8 Feb.	"	4-4
	10 Feb.	"	4-5
6	13 Feb.	"	4-6 thru 4-8 Lab: Cap Design
	15 Feb.	"	4-9, 4-10
	17 Feb.	"	4-11 (and review)
7	20 Feb.	Magnetostatics	5-1
	22 Feb.	"	5-2 (Night Exam in 112 Kern)
	24 Feb.	"	5-3
8	27 Feb.	"	5-4 thru 5-6 Lab: Nuclear Inspector
	29 Feb.	"	5-7, 5-8
	2 Mar.	Maxwell's Equations (for time-varying)	6-1, 6-2
		SPRING BREAK !!!!	
9	12 Mar.	"	6-3, 6-4
	14 Mar.	"	6-5, 6-6
	16 Mar.	"	6-7 thru 6-10 (look at 6-11)
10	19 Mar.	Plane-Wave Propagation	7-1 Lab: Transformers
	21 Mar.	"	7-2
	23 Mar.	"	7-3
11	26 Mar.	"	7-4
	28 Mar.	"	7-5
	30 Mar.	"	7-6 (and review)
12	2 Apr.	Reflection, Transmission, & Waveguides	8-1, 8-2 (look at 8-3)
	4 Apr.	"	8-4 (Night Exam, 22 Dieke)
	6 Apr.	"	8-4 (again), 8-5
13	9 Apr.	"	8-6, 8-7 Lab: The Tomb
	11 Apr.	"	8-8, 8-9
	13 Apr.	"	8-10, 8-11
14	16 Apr.	Radiation and Antennas	9-1
	18 Apr.	"	9-2
	20 Apr.	"	9-3, 9-4
15	23 Apr.	"	9-5, 9-6 Lab: Antennas
	25 Apr.	"	9-7, 9-8
	27 Apr.	"	9-9 thru 9-11



# Fundamentals of Applied Electromagnetics

4th ed.



check out Figure 1-2 ☺

FARUQ T. ULABY | ERIC MICHELSSEN | DANIEL D. RAJAN

...and the Tech Briefs too!!

**ca. 900 BC** Legend has it that while walking across a field in northern Greece, a shepherd named Magnus experiences a pull on the iron nails in his sandals by the black rock he was standing on. The region was later named **Magnesia** and the rock became known as **magnetite** [a form of iron with permanent magnetism].

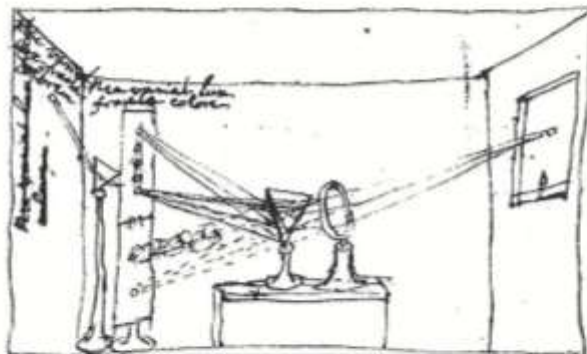
**ca. 600 BC** Greek philosopher **Thales** describes how amber, after being rubbed with cat fur, can pick up feathers [static electricity].

**ca. 1000** Magnetic compass used as a navigational device.



**1600** **William Gilbert** (English) coins the term **electric** after the Greek word for amber (elektron), and observes that a compass needle points north-south because the Earth acts as a bar magnet.

**1671** **Isaac Newton** (English) demonstrates that **white light** is a mixture of all the colors.



**1733** **Charles-Francois du Fay** (French) discovered that **electric charges** are of two forms, and that like charges repel and unlike charges attract.

**1745** **Pieter van Musschenbroek** (Dutch) invents the Leyden jar, the first electrical **capacitor**.

**1752** **Benjamin Franklin** (American) invents the **lightning rod** and demonstrates that lightning is electricity.

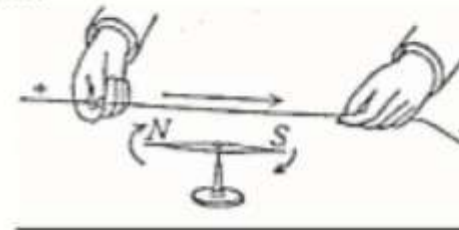


**1785** **Charles-Augustin de Coulomb** (French) demonstrates that the **electrical force** between charges is proportional to the inverse of the square of the distance between them.

**1800** **Alessandro Volta** (Italian) develops the first **electric battery**.



**1820** **Hans Christian Oersted** (Danish) demonstrates the **interconnection** between electricity and magnetism through his discovery that an electric current in a wire causes a compass needle to orient itself perpendicular to the wire.



<http://www.youtube.com/watch?v=c3WWAghWbjo>

**1820** **Andre-Marie Ampere** (French) notes that **parallel currents** in wires attract each other and **opposite currents** repel.

**1820** **Jean-Baptiste Biot** (French) and **Felix Savart** (French) develop the **Biot-Savart law** relating the magnetic field induced by a wire segment to the current flowing through it.



1827 **Georg Simon Ohm** (German) formulates **Ohm's law** relating electric potential to current and resistance.

1827 **Joseph Henry** (American) introduces the concept of **inductance** and built one of the earliest electric motors. He also assisted Samuel Morse in the development of the **telegraph**.



1831 **Michael Faraday** (English) discovers that a changing magnetic flux can induce an **electromotive force**.

1835 **Carl Friedrich Gauss** (German) formulates **Gauss's law** relating the electric flux flowing through an enclosed surface to the enclosed electric charge.

*Gauss' Law for Electricity*

$$\Phi_E = \oint \vec{E} \cdot d\vec{A} = \frac{q_{\text{inside}}}{\epsilon_0}$$

1873 **James Clerk Maxwell** (Scottish) publishes his *Treatise on Electricity and Magnetism* in which he unites the discoveries of Coulomb, Oersted, Ampere, Faraday, and others into four elegantly constructed mathematical equations known today as **Maxwell's Equations**.



1887



**Heinrich Hertz** (German) builds a system that can generate **electromagnetic waves** (at radio frequencies) and detect them.

1888 **Nikola Tesla** (Serbian-American) invents the **ac** (alternating current) electric motor.

1895 **Wilhelm Roentgen** (German) discovers **X-rays**. One of his first X-ray images was of the bones in his wife's hand. [1901 Nobel Prize in physics.]

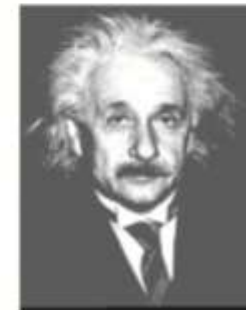
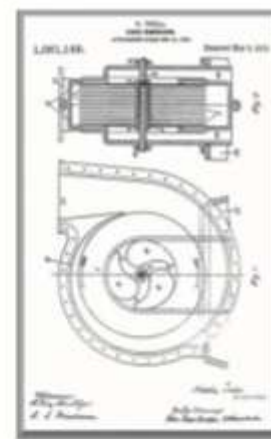


1897 **Joseph John Thomson** (English) discovers the **electron** and measures its charge-to-mass ratio. [1906 Nobel Prize in physics.]

1905 **Albert Einstein** (German-American) explains the **photoelectric effect** discovered earlier by Hertz in 1887. [1921 Nobel Prize in physics.]



*Einstein*



<http://www.youtube.com/watch?v=Zi4kXgDBFhw&NR=1>



1825



**William Sturgeon** (English) develops the multi-turn **electromagnet**.

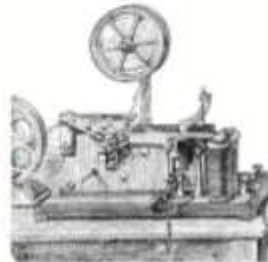
1896



**Guglielmo Marconi** (Italian) files his first of many patents on **wireless transmission** by radio. In 1901, he demonstrates **radio telegraphy** across the Atlantic Ocean. [1909 Nobel Prize in physics, shared with Karl Braun (German).]

1837

**Samuel Morse** (American) patents the **electromagnetic telegraph**, using a code of dots and dashes to represent letters and numbers.



1897

**Karl Braun** (German) invents the **cathode ray tube (CRT)**. [1909 Nobel Prize with Marconi.]

1872

**Thomas Edison** (American) patents the **electric typewriter**.

1902

**Reginald Fessenden** (American) invents **amplitude modulation** for telephone transmission. In 1906, he introduces **AM radio broadcasting** of speech and music on Christmas Eve.

1876

**Alexander Bell** (Scottish-American) invents the **telephone**, the rotary dial becomes available in 1890, and by 1900 telephone systems are installed in many communities.



1912

**Lee De Forest** (American) develops the **triode tube** amplifier for wireless telegraphy. Also in 1912, the wireless distress call issued by the Titanic was heard 58 miles away by the ocean liner Carpathia which managed to rescue 705 Titanic passengers 3.5 hours later.



1887

**Heinrich Hertz** (German) generates **radio waves** and demonstrates that they share the same properties as light.



1887

**Emil Berliner** (American) invents the flat gramophone disc, or **record**.

1919

**Edwin Armstrong** (American) invents the **superheterodyne radio receiver**.

1893

**Valdemar Poulsen** (Danish) invents the first **magnetic sound recorder** using steel wire as recording medium.



1920

Birth of **commercial radio broadcasting**; Westinghouse Corporation establishes radio station KDKA in Pittsburgh, Pennsylvania.



<http://www.youtube.com/watch?v=6ybYxkt3UxU>

1923



**Vladimir Zworykin** (Russian-American) invents **television**. In 1926, John Baird (Scottish) transmits TV images over telephone wires from London to Glasgow. Regular **TV broadcasting** began in Germany (1935), England (1936) and the U.S. (1939).

1958

**Jack Kilby** (American) builds first **integrated circuit (IC)** on germanium and, independently, **Robert Noyce** (American) builds first IC on silicon.



1960



**Echo**, the first passive communication satellite is launched, and successfully reflects radio signals back to Earth. In 1963, the first **communication satellite** is placed in geosynchronous orbit.

1926

**Transatlantic telephone** service between London and New York.

1932

First **microwave telephone link**, installed (by Marconi) between Vatican City and the Pope's summer residence.

1933

**Edwin Armstrong** (American) invents **frequency modulation (FM)** for radio transmission.

1935

**Robert Watson Watt** (Scottish) invents **radar**.



1938

H. A. Reeves (American) invents **pulse code modulation (PCM)**.

1947

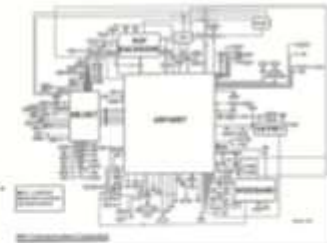
**William Schockley, Walter Brattain and John Bardeen** (all American) invent the junction **transistor** at Bell Labs. [1956 Nobel Prize in physics.]



1979

Japan builds the first **cellular telephone network**.

- 1983 cellular phone networks start in the U.S.
- 1990 **electronic beepers** become common
- 1995 **cell phones** become widely available
- 2002 cell phone supports **video and internet**



1984

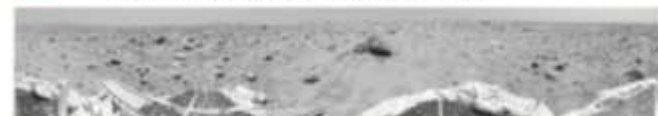
Worldwide **Internet** becomes operational.

1988

First **transatlantic optical fiber cable** between the U.S. and Europe.

1997

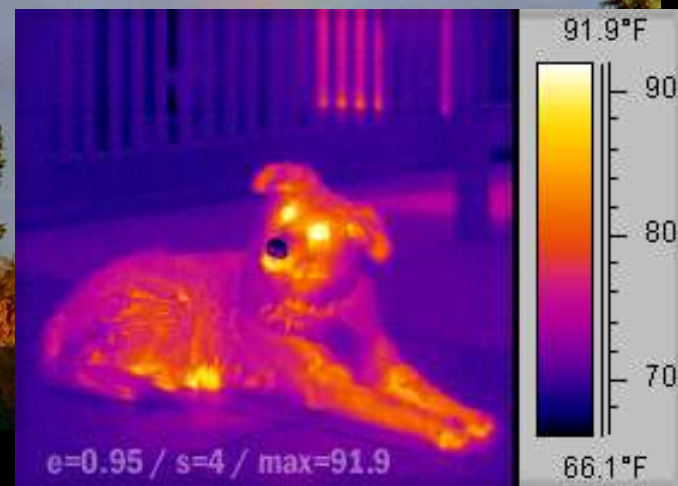
Mars Pathfinder sends images to Earth.



2004

**Wireless communication** supported by many airports, university campuses, and other facilities.

<http://www.youtube.com/watch?v=U5aVw9hu6IQ>

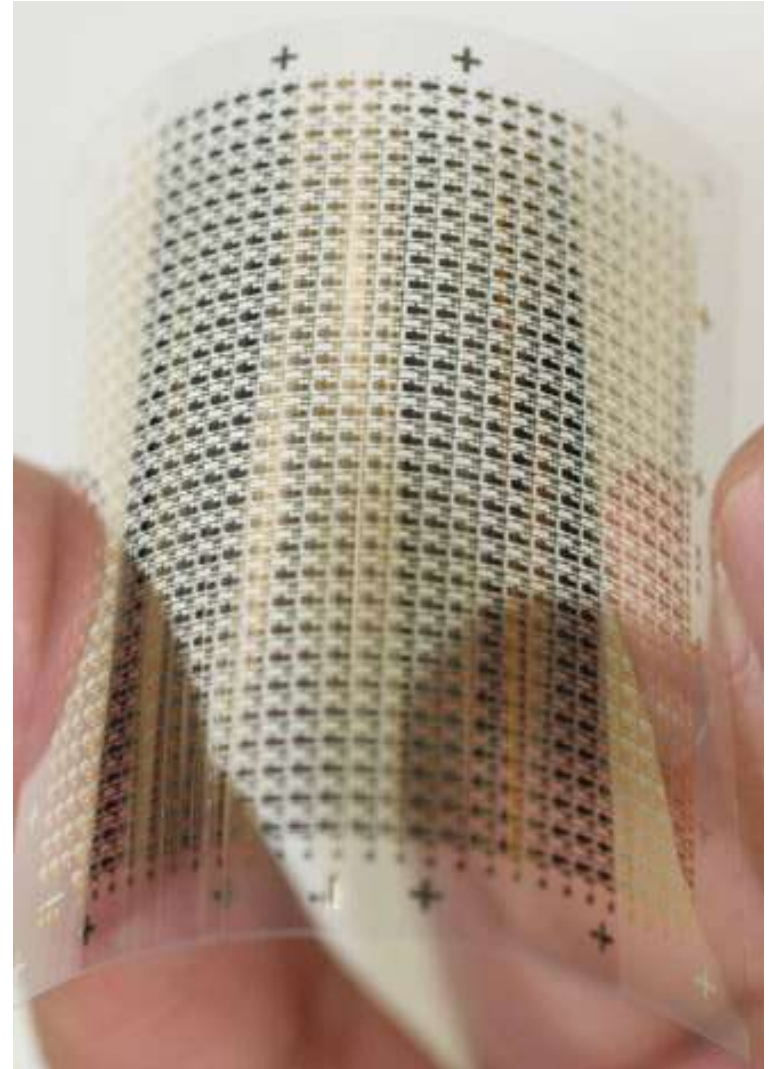




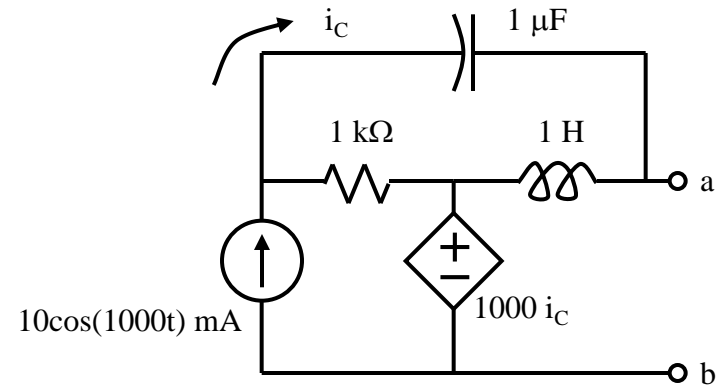
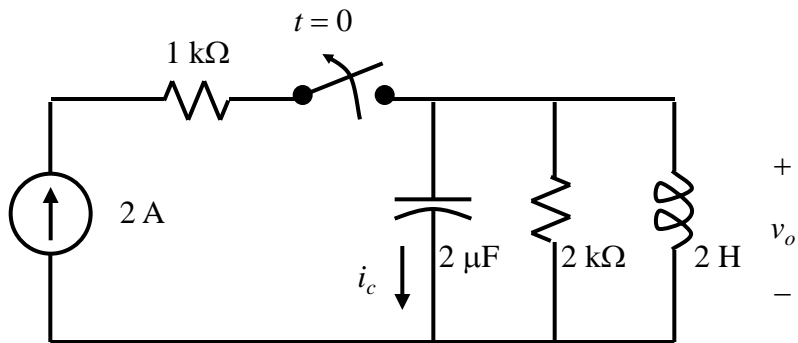


<http://spectrum.ieee.org/>

## Flexible Flash Memory



## Why is EE 210 (circuits) a pre-requisite???





# Why is Math 230 or 232 (calculus & vector analysis) a pre-requisite???

## Summary of Vectors, Dot Products and Cross Products

- A vector is a directed line segment translated so that the initial point is at the origin. They have two different notations.

$\mathbf{u} = \langle u_1, u_2, u_3 \rangle$  called component form,

and

$\mathbf{u} = u_1\mathbf{i} + u_2\mathbf{j} + u_3\mathbf{k}$  where  $\mathbf{i} = \langle 1, 0, 0 \rangle$ ,  $\mathbf{j} = \langle 0, 1, 0 \rangle$ , and  $\mathbf{k} = \langle 0, 0, 1 \rangle$

- The vector from  $P(x_0, y_0, z_0)$  to  $Q(x_1, y_1, z_1)$  is given by

$$\mathbf{u} = \overrightarrow{PQ} = \langle x_1 - x_0, y_1 - y_0, z_1 - z_0 \rangle$$

- The **length**, **magnitude**, or **norm** of  $\mathbf{u}$  is given by  $\|\mathbf{u}\| = \sqrt{u_1^2 + u_2^2 + u_3^2}$
- The **unit vector** in the direction of  $\mathbf{v}$  is given by  $\mathbf{u} = \frac{\mathbf{v}}{\|\mathbf{v}\|}$

Let  $\mathbf{u} = \langle u_1, u_2, u_3 \rangle$  and  $\mathbf{v} = \langle v_1, v_2, v_3 \rangle$  and  $\mathbf{w} = \langle w_1, w_2, w_3 \rangle$

- **Dot Product:**  $\mathbf{u} \cdot \mathbf{v} = u_1v_1 + u_2v_2 + u_3v_3 = \|\mathbf{u}\| \|\mathbf{v}\| \cos(\theta)$ , where  $\theta$  is the angle between  $\mathbf{u}$  and  $\mathbf{v}$ .

**Major Property:** The vectors  $\mathbf{u}$  and  $\mathbf{v}$  are **orthogonal** (perpendicular) if and only if  $\mathbf{u} \cdot \mathbf{v} = 0$ .

- **Cross Product:**  $\mathbf{u} \times \mathbf{v} = (u_2v_3 - u_3v_2)\mathbf{i} - (u_1v_3 - u_3v_1)\mathbf{j} + (u_1v_2 - u_2v_1)\mathbf{k}$

**Major property:**  $\mathbf{u} \times \mathbf{v}$  is orthogonal to both  $\mathbf{u}$  and  $\mathbf{v}$

**magnitude of cross product:**  $\|\mathbf{u} \times \mathbf{v}\| = \|\mathbf{u}\| \|\mathbf{v}\| \sin(\theta)$

# What's an electric field??

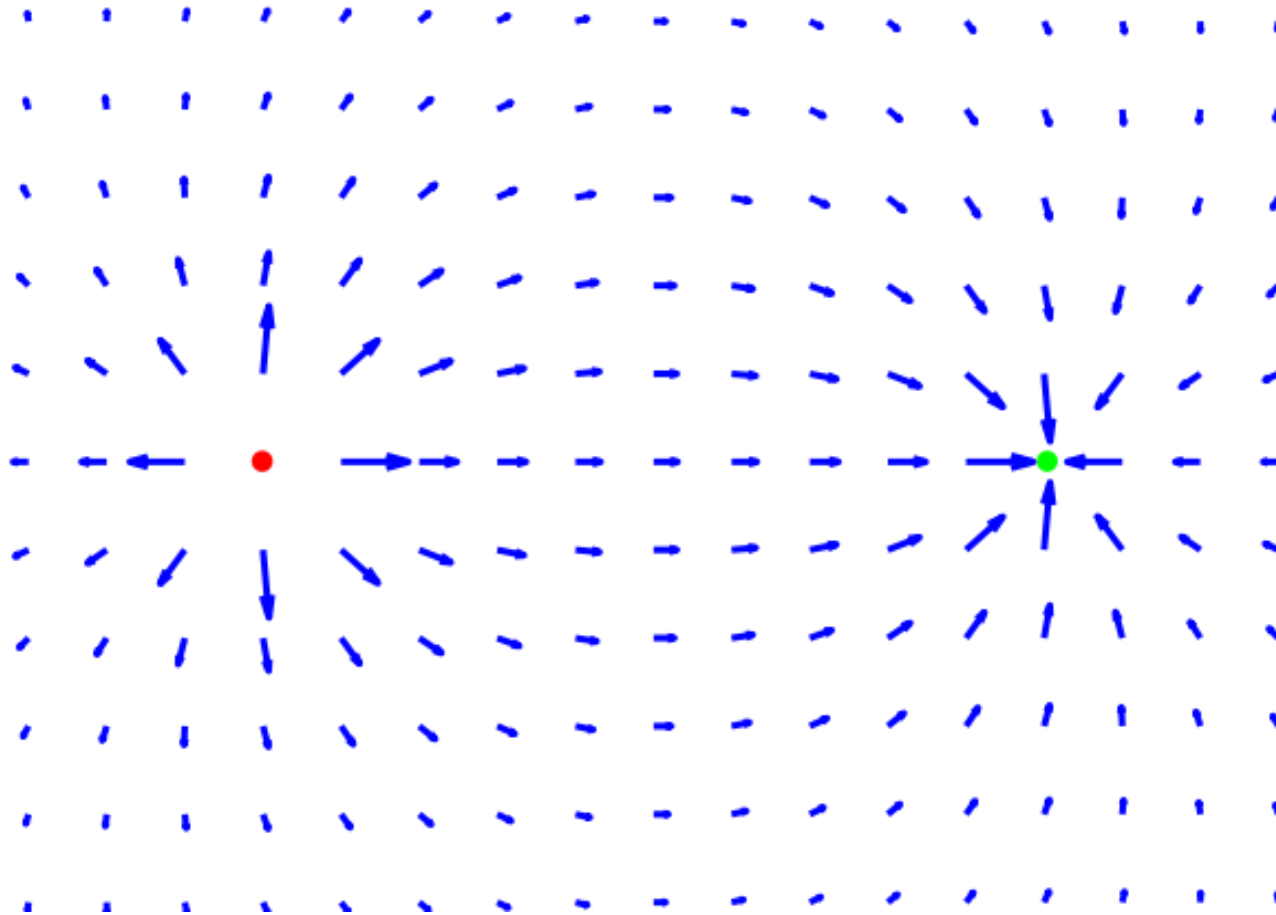
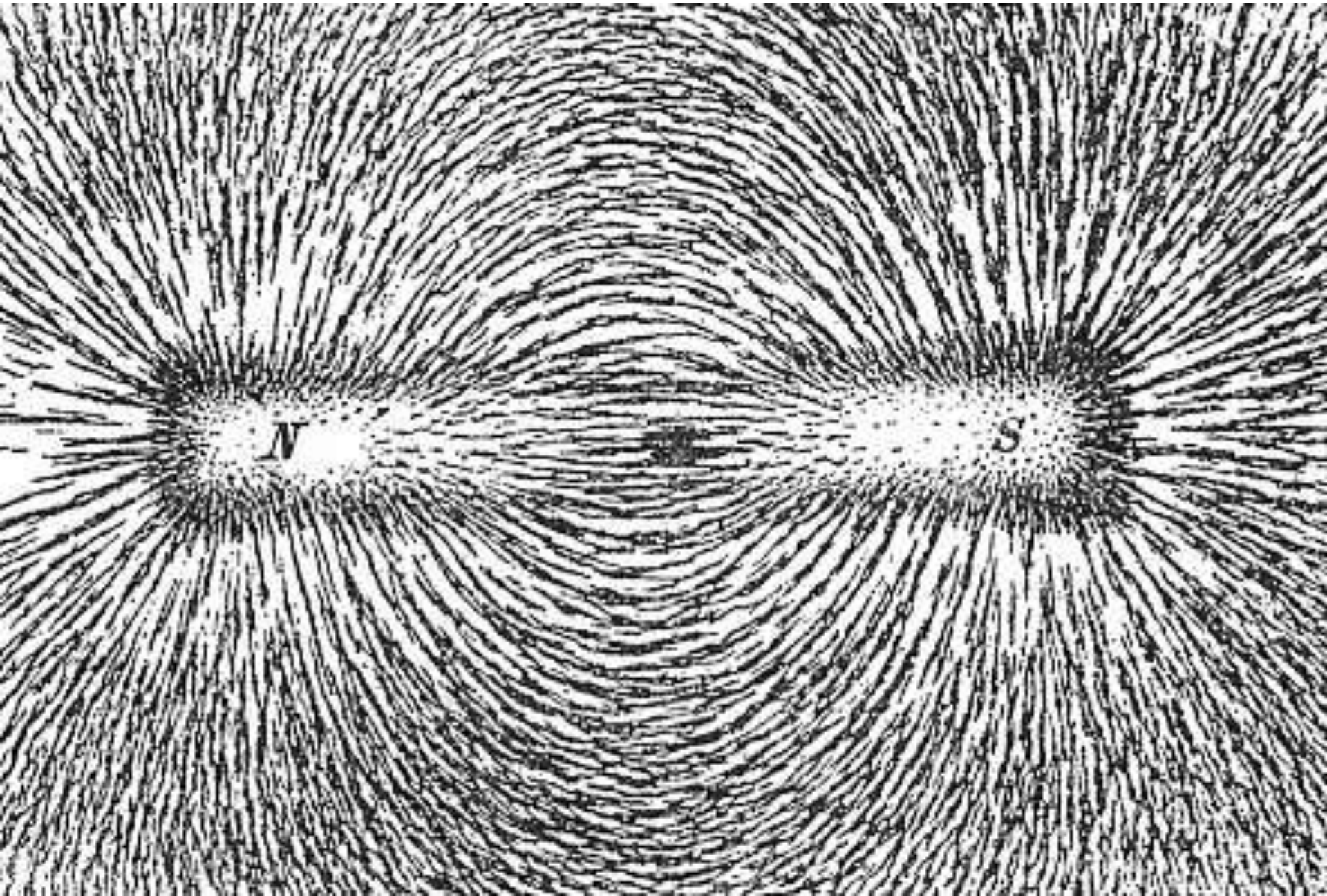


Illustration of the electric field surrounding a positive (red) and a negative (green) charge.

<http://www.cco.caltech.edu/~phys1/java/phys1/EField/EField.html>



**How about a magnetic field??**



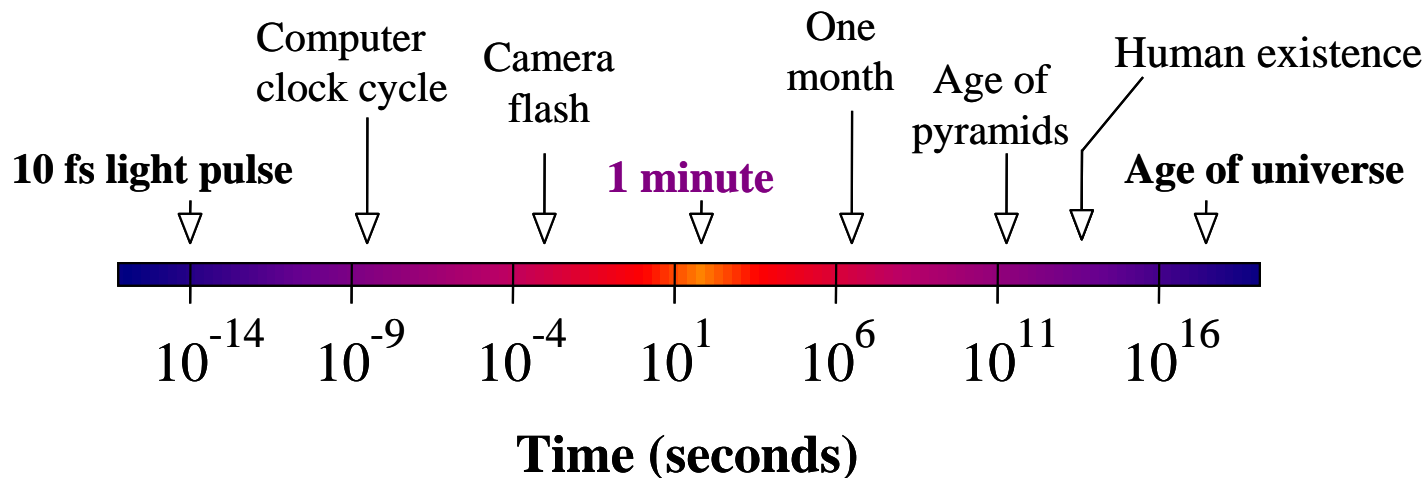
**Table 1-1:** Fundamental SI units.

Dimension	Unit	Symbol
Length	meter	m
Mass	kilogram	kg
Time	second	s
Electric Current	ampere	A
Temperature	kelvin	K
Amount of substance	mole	mol

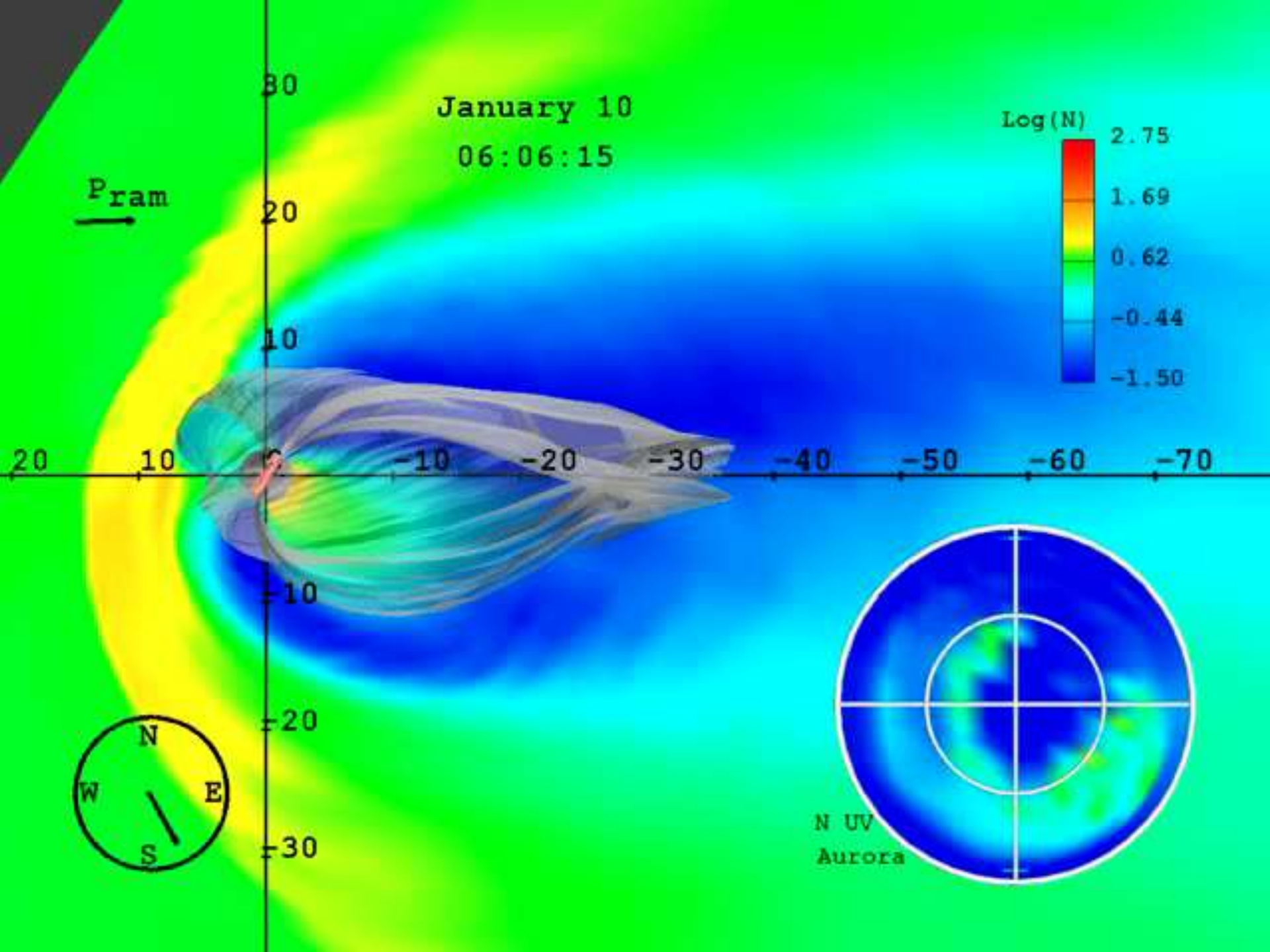
10 fs is to 1 minute as  
1 minute is to the age  
of the universe.

**Table 1-2:** Multiple and submultiple prefixes.

Prefix	Symbol	Magnitude
exa	E	$10^{18}$
peta	P	$10^{15}$
tera	T	$10^{12}$
giga	G	$10^9$
mega	M	$10^6$
kilo	k	$10^3$
milli	m	$10^{-3}$
micro	$\mu$	$10^{-6}$
nano	n	$10^{-9}$
pico	p	$10^{-12}$
femto	f	$10^{-15}$
atto	a	$10^{-18}$







**HW 1:**      *Due Friday 13 January*

1.3, 1.7, 1.13, 1.17, 1.29





## Queries

How many numbers do you need to describe the temperature at some point in the classroom?

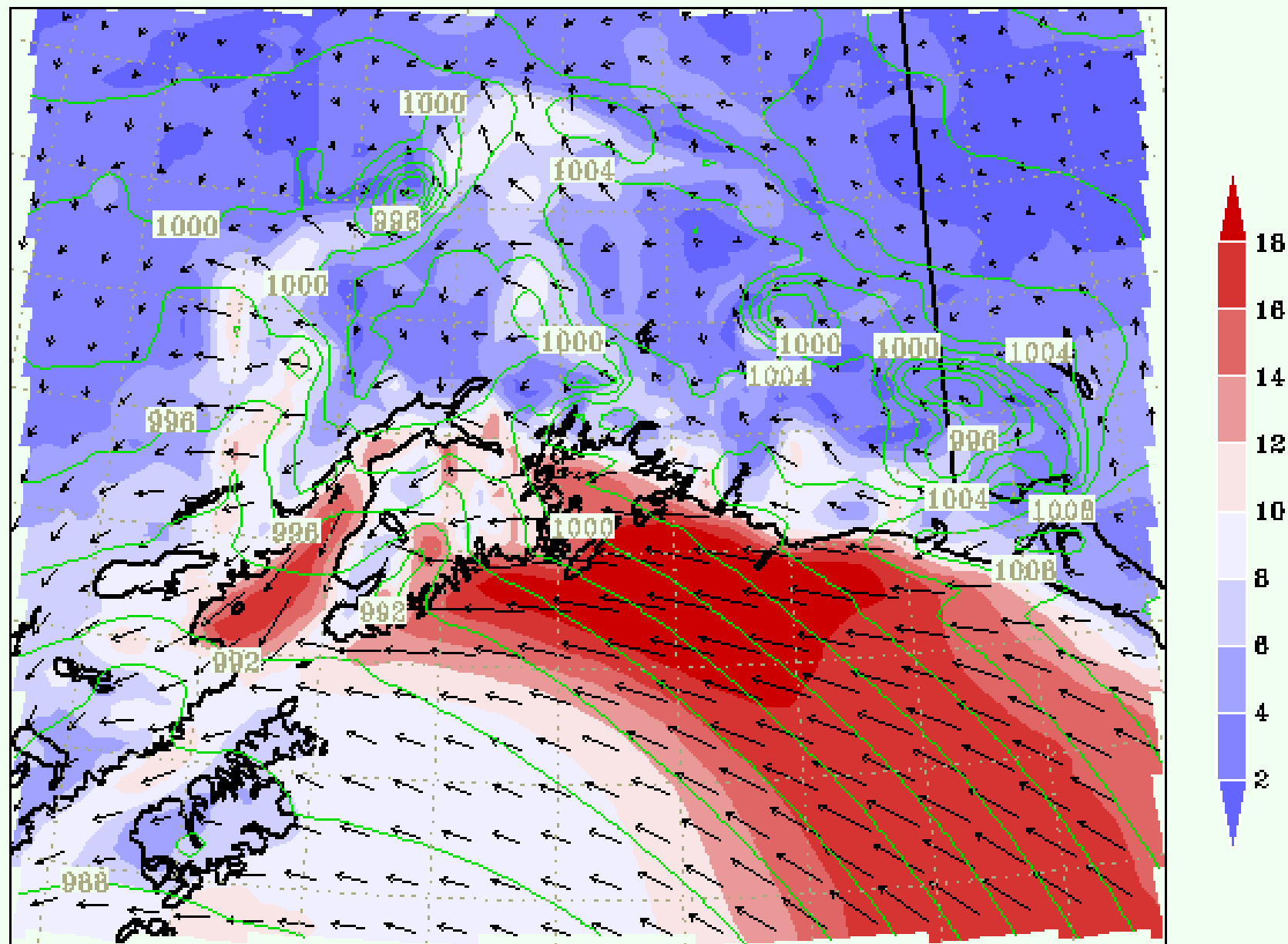
Is there an electric field in the room?

How about magnetic?

How many numbers do you need to describe these?



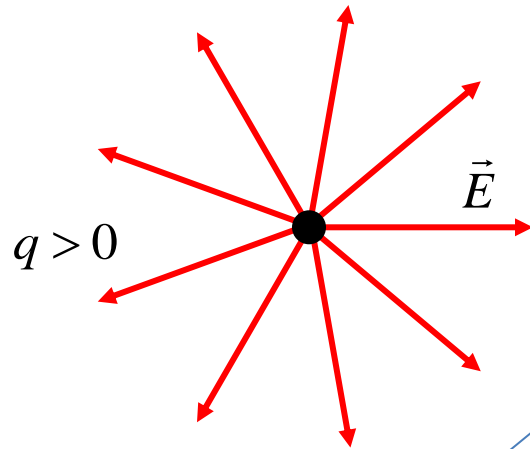
# vectors



valid 08/28/01 18Z

20

$$\vec{E} = \hat{r} \frac{q}{4\pi\epsilon R^2}$$



Oscillations, waves, etc.  
(time-varying fields)



# The World is Complex

$$j \equiv \sqrt{-1}$$

or  $i$  is too

$$Z = a + jb$$

$$w/ a \equiv \operatorname{Re}\{Z\}$$

$$b \equiv \operatorname{Im}\{Z\}$$

Examples:

$$Z = 1 + 2j$$

$$Z = 0 + j = j$$

$$Z = 4.3 + 0j = 4.3$$

(which are all in Rectangular form)

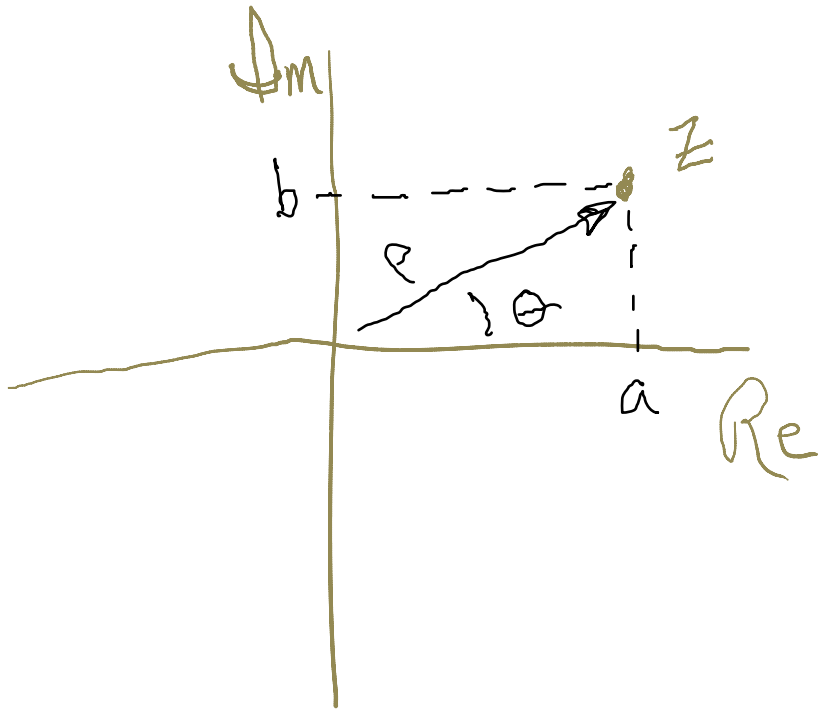
Euler

$$e^{j\theta} = \cos \theta + j \sin \theta$$



can write any complex # in polar form!

$$Z = p e^{j\theta} = \underbrace{p \cos \theta}_a + j \underbrace{p \sin \theta}_b$$



$$a = p \cos \theta$$

$$b = p \sin \theta$$

$$a^2 + b^2 = |Z|^2 = p^2$$

$$\tan \theta = \frac{b}{a}$$

Note: Angles in Radians

$2\pi$  Radians in a circle

$$\Rightarrow \pi \text{ radians} = 180^\circ$$

Examples

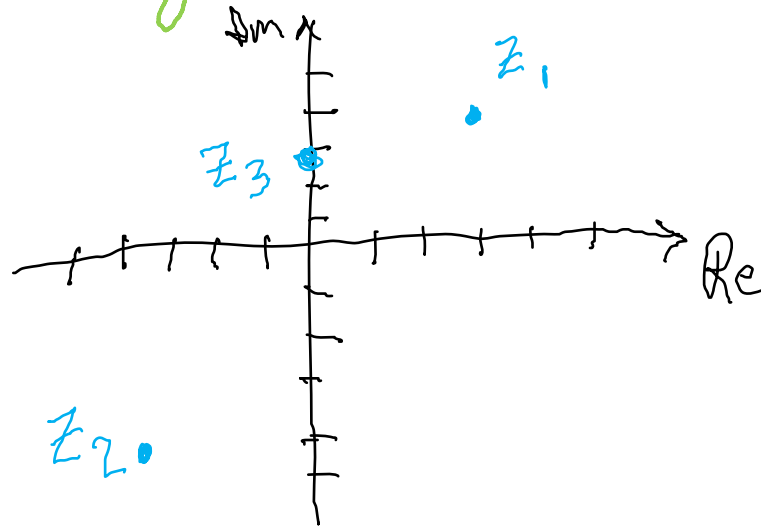
$$z_1 = 3 + j4 = 5e^{j53.13^\circ} = 5e^{j0.93}$$

$$z_2 = -3 - j4 = 5e^{-j126.87^\circ}$$

$$z_3 = 3j = 3e^{j90^\circ} = 3e^{j\frac{\pi}{2}}$$

Radians

stay between  
 $+180^\circ$   
 $(+\pi \text{ rads})$



Note:  $e^{j\theta} = e^{j(\theta+2\pi)} = e^{j(\theta \pm n2\pi)}$  for  $n$  integer

---

$$z_1 = a + jb = \rho_1 e^{j\theta_1}, \quad z_2 = c + jd = \rho_2 e^{j\theta_2}$$

$$\Rightarrow z_1 + z_2 = (a+c) + j(b+d)$$

$$z_1 \cdot z_2 = \rho_1 \rho_2 e^{j(\theta_1 + \theta_2)}$$

$$z_1 / z_2 = \rho_1 / \rho_2 e^{j(\theta_1 - \theta_2)}$$

$$z_1^n = \rho_1^n e^{jn\theta_1} \quad \text{for all } n$$

Finally,  $e^{j\pi} = -1$

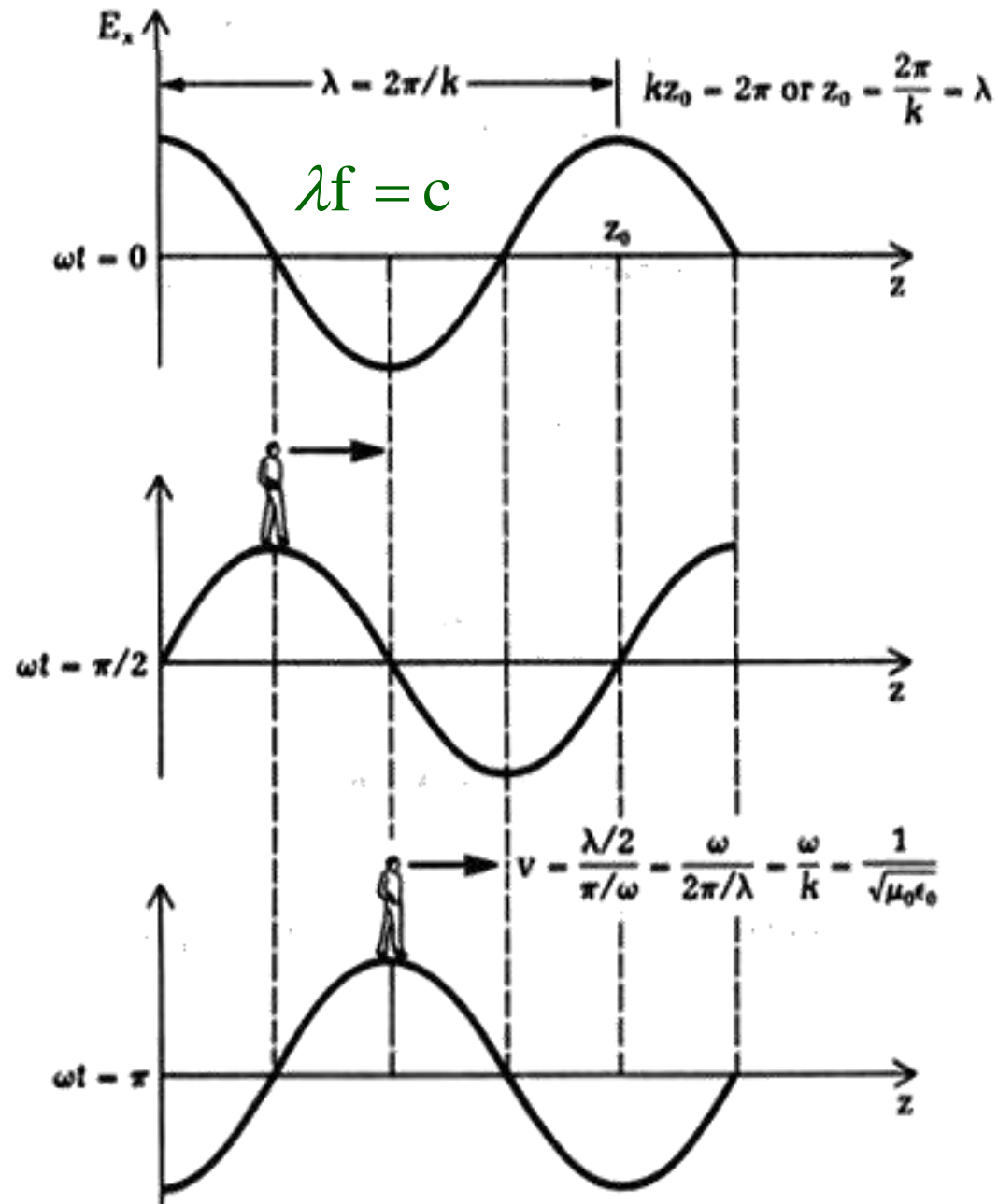
$$z^* = a - jb \quad \text{complex conjugate} \quad |z|^2 = z z^*$$



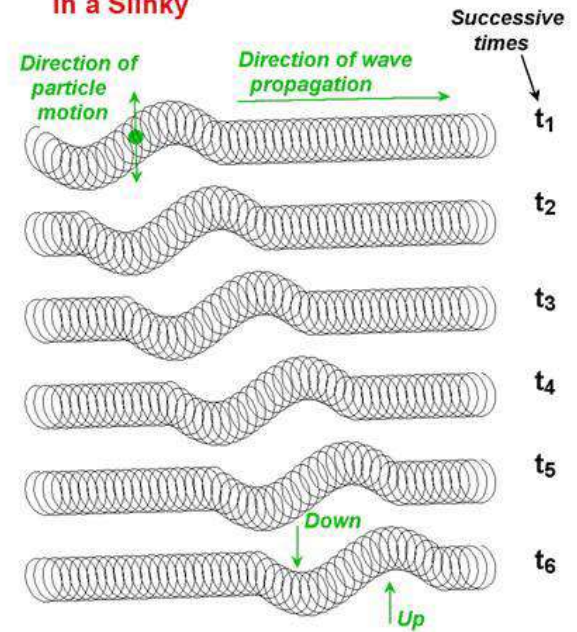
$$\vec{E}(x, y, z, t) = E_0 \cos[\omega t - kz] \hat{x}$$

<http://www.falstad.com/ripple/>

**Note: these are scalar examples !!**



### Shear (S) Wave Propagation in a Slinky



$$\vec{E} = \hat{x} E_0 e^{-\alpha z} e^{-j\beta z}$$

$$= \hat{x} E_0 e^{-\alpha z} \cos(\omega t - \beta z)$$

# Phasors

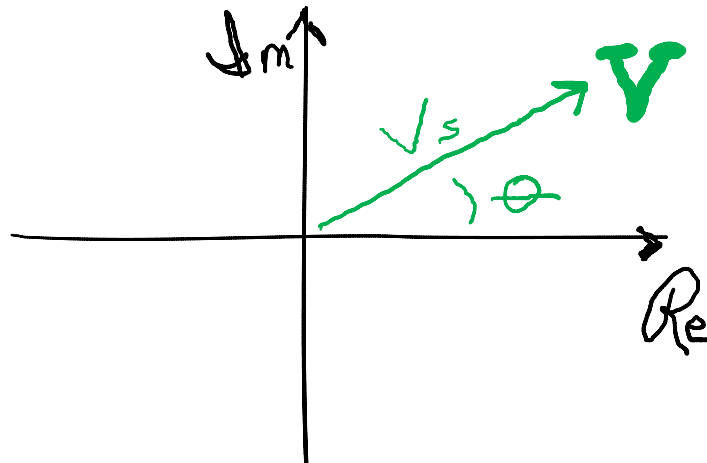
with  $\omega \equiv 2\pi f$   
(Rad/s) (Hz)

Sinusoidal Response  $v(t) = V_s \cos(\omega t + \theta)$   
(Time Domain)

Complex Sinusoidal Response  $v(t) = V_s e^{j(\omega t + \theta)}$

Phasor Representation  $\mathbf{V} = V_s e^{j\theta} \equiv V_s \angle \theta$

Assuming  $\omega$  is constant



which is why we care about complex #s 😊

Example 1  $E_1(t) = 100 \cos(\omega t + 45^\circ)$ ,  $E_2(t) = 100 \sin(\omega t + 60^\circ)$

what is  $E_1(t) + E_2(t) = 100 \cos(\omega t + 45^\circ) + 100 \sin(\omega t + 60^\circ)$  ??

FIRST,  $E_2(t) = 100 \underline{\cos}(\omega t - 30^\circ)$   $\leftarrow$  why??

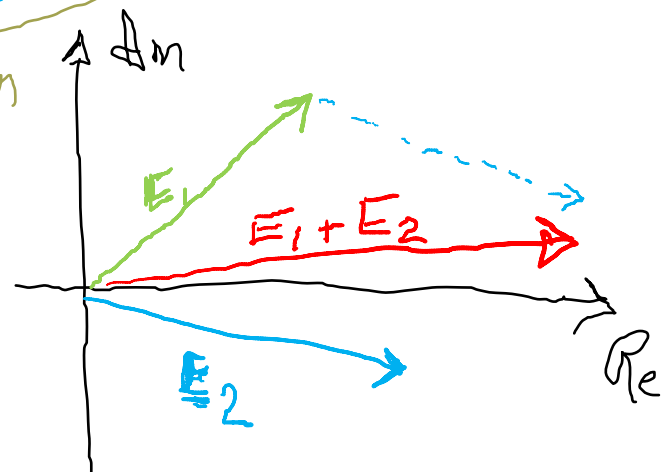
Phasors,  $E_1 = 100 \angle 45^\circ$ ,  $E_2 = 100 \angle -30^\circ$

Note: make sure your calculator is happy with complex #'s

$$E_1 + E_2 = \{100 \cos 45^\circ + 100 \cos(-30^\circ)\} + j\{100 \sin 45^\circ + 100 \sin(-30^\circ)\}$$

$$= \underbrace{157.3 + j20.71}_{\text{Rectangular form}} = \underbrace{158.7 \angle 7.5^\circ}_{\text{Polar form}}$$

$$\Rightarrow E_1(t) + E_2(t) = \underbrace{158.7 \cos(\omega t + 7.5^\circ)}_{\text{Time domain...}}$$



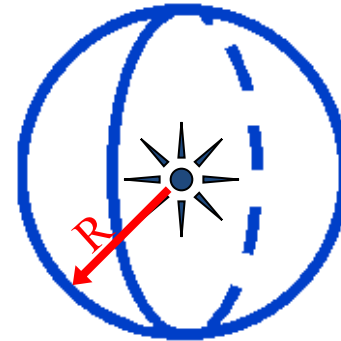
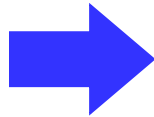


### Example:

Assume a 100 W light bulb is *really* small and gives off light with 100% efficiency.

♦ What is the power density a distance 10m from the lamp?

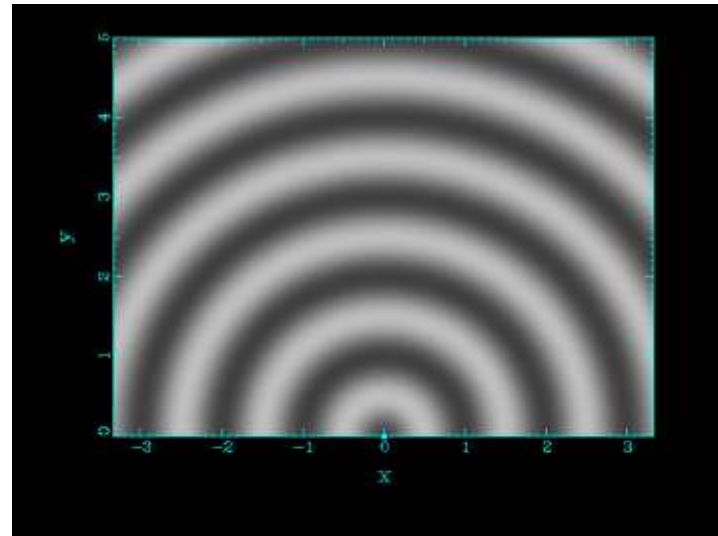
Isotropic  
Radiator



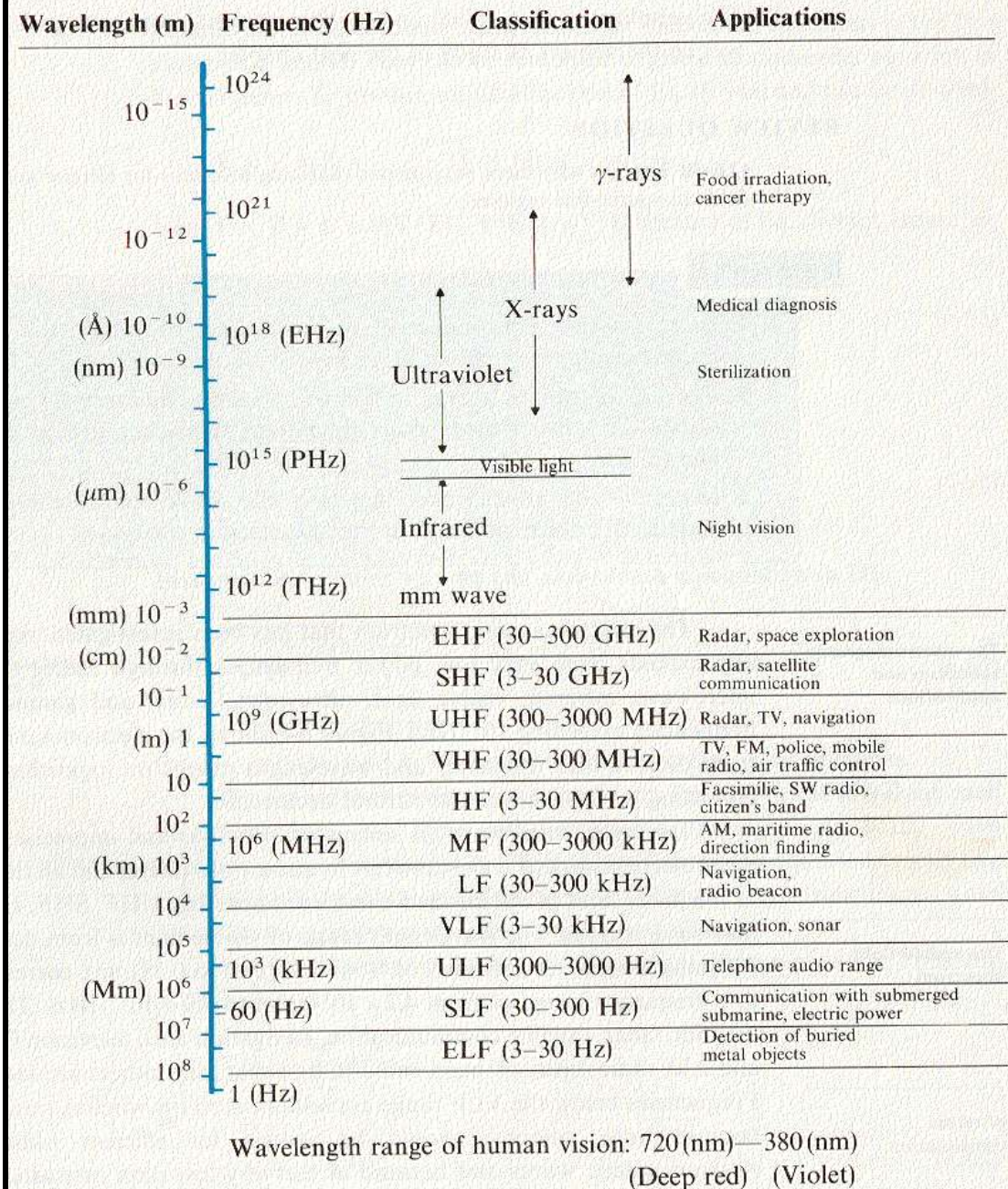
Distribute radiated  
power over surface  
area of sphere  $= 4\pi R^2$

Note:  $R^2$  factor  
very important!

$$powerdensity = \frac{100W}{4\pi \times 10^2 m^2} = 0.08 \frac{W}{m^2}$$



Band	Frequency	Wavelength
HF	3-30 MHz	100 - 10 m
VHF	30 - 300 MHz	10 - 1 m
UHF	300 - 1000 MHz	1 - 0.3 m
L	1 - 2 GHz	30 - 15 cm
S	2 - 4 GHz	15 - 8 cm
C	4 - 8 GHz	8 - 4 cm
X	8 - 12 GHz	4 - 2.5 cm
K <sub>u</sub>	12 - 18 GHz	2.5 - 1.7 cm
K	18 - 27 GHz	1.7 - 1.2 cm
K <sub>a</sub>	27 - 40 GHz	1.2 - 0.75 cm
mm	40 - 300 GHz	7.5 - 1 mm
T-waves		
IR	15 - 430 THz	0.7 – 20 $\mu\text{m}$
visible	430 – 750 THz	400-700 nm
UV	750 – 1500 THz	200 – 400 nm





# But 1<sup>st</sup>!

